

Variety in Supernovae

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Abstract. Detailed observations of a growing number of supernovae have determined a bloom of new peculiar events. In this paper we take a short tour through the SN diversity and discuss some important, physical issues related to it. Because of the role of SN Ia in determining the cosmological parameters, it is crucial to understand the physical origin of even subtle, observed differences. An important issue is also the reddening correction. We believe that the measure of interstellar lines on medium resolution spectra of SNe can be used to derive lower limits on the interstellar extinction. A few physical parameters of the progenitor, namely radius, mass, density structure and angular momentum, may explain most of the diversity of core-collapse events. In addition, if the ejecta expand into a dense circumstellar medium the ejecta-CSM interaction may dominate the observed outcome and provide a mean to probe the mass loss history of the SN progenitor in the last stages of its evolution.

1 Introduction

Despite the natural inclination of human brain to simplify and group phenomena in a numerable amount of classes, there is no doubt that nature is complex, and its complexity increases the more we understand. This is valid also in astrophysics and, in particular, in the field of Supernovae (SNe). After the early decades in which the researchers were discovering the universe of cosmic explosions and phenomenologically grouped them in an handful of types, we are at a stage in which the detailed analysis shows the individuality of each event. This does not necessarily contradict previous findings, just reflects our ability to detect, and partially understand, subtler details. Indeed, if up to the 1980s it was possible to isolate only the two major SN types, the utilization of linear detectors has lead to a florilegium of types and subtypes. The present classification scheme is complex [1] and accounts, in addition to the intrinsic nature of the explosion mechanisms and progenitors, also for phenomena occurring after the explosion which can dramatically affect the SN display, e.g. the interaction of the ejecta with the circumstellar matter. In the following we discuss some of the most significant issues related to the variety of the SNe.

2 The Diversity of Type Ia SNe

The thermonuclear explosions of accreting white dwarfs produce type Ia SNe, which owing to their high luminosity and accurate calibration are successfully

used for determining the geometry of the Universe [2]. This is not to say that SN Ia are standard candles. In fact, even after excluding a number of extreme events or outliers (e.g. SN 1991bg or 1991T), spectroscopic and photometric differences among SN Ia do remain. However, empirical relations between the light curve shape and the luminosity at maximum [3–6] allow to recover type Ia SNe as the best distance indicators up to cosmological distances.

Where the variance of SN Ia comes from is not yet known even if it probably involves differences in the structure and composition of the precursor WD. Analysis of the very early spectra of SN Ia could give fundamental insights in this respect. Unfortunately, because of the very steep rise of luminosity, observing SNIa before maximum is a very demanding task. To address this and other issues related to the physics of type Ia supernovae a new European collaboration has just started (RTN2-2001-00037) which had a cold start with the extensive observations of the early stages of three events, SNe 2002bo, 2002dj and 2002er.

The first data to be analyzed are those of SN 2002bo. The B–V color curve of SN 2002bo is compared in Fig. 1 with those of three other well studied SN Ia after correction for reddening. Indeed, following [6] a total reddening $E(B-V)=0.48$ mag was estimated for SN 2002bo. This is not unexpected since this SN exploded close to the dust lane of NGC 3190, which obscured SN 2002cv by more than 6 magnitudes [7]. All objects in the figure show the color evolution typical of SN Ia. However, a closer examination of Fig. 1 shows that significant differences in the individual behaviors do exist. For instance, note that SN 1994D reaches its reddest color about 20–25 days after maximum light, i.e. 10 days before SN 1999ee. Other differences are found in the premaximum evolution: while SN 1999ee shows a monotonic reddening starting at least 10 days before maximum, SN 1994D and more clearly SN 2002bo, are very red in the earliest epochs and reach a minimum (blue) color 3–5 days before maximum.

Actually red colors in the early phases of SNIa are predicted by theoretical models [11,12]. This is because the decrease of temperature due to adiabatic cooling occurs before the heating, due to the γ -rays from ^{56}Ni to ^{56}Co radioactive decay, reaches the photosphere. Since at such epochs the observations sample the outermost layers of the exploding stars, the differences in the observed color evolution might reflect differences in the progenitors structure and composition.

Similar considerations can be drawn from the analysis of the spectra. In Fig. 2 are shown four of the earliest available spectra of SNIa (ranging between 14 to 10 days before maximum, that is less than a week from explosion). Although even small age differences may explain part of the observed diversity, there is no doubt that intrinsic differences exist. In particular, around 6000 Å we note the different profiles of the SiII absorption which in SN 1990N has a flat bottom attributed to the contribution of high velocity CII [13]. Even more striking is the diversity in the blue side where entire absorption bands which are visible in SN 2002dj, 2002bo and SN 1994D, e.g. that due to SiII 4128, 4131, CoII 4161, are absent in SN 1990N. A detailed analysis of the sequence of early spectra of SNe 2002bi and 2002dj is in progress.

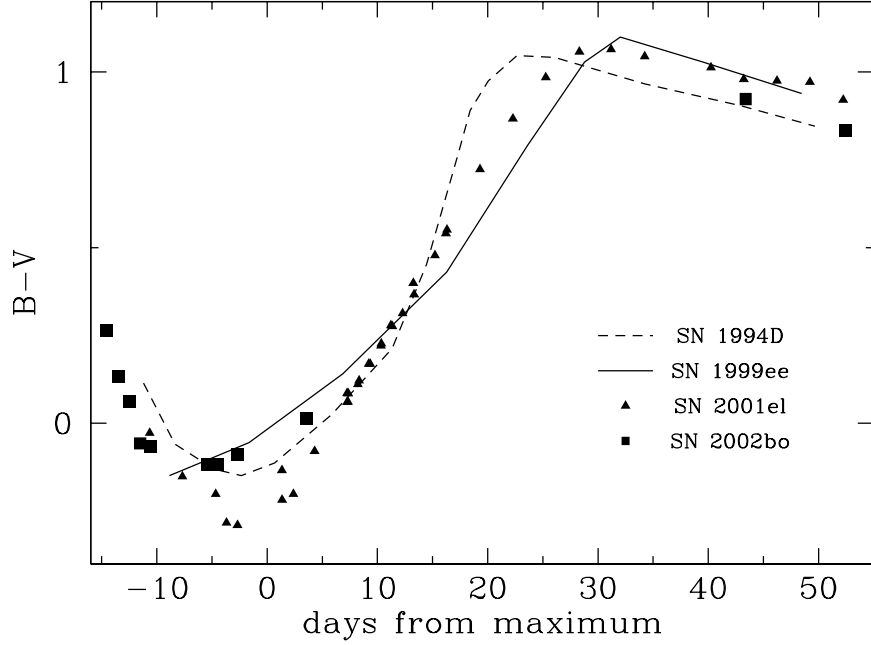


Fig. 1. Comparison of the preliminary B-V light curve of SN 2002bo with those of other normal SNIa, SNe 1994D [8], 1999ee [9] and 2001el [10]. The color curves have been dereddened according to [6]

It should be stressed that the claims of an accelerated expansion of the Universe relies on the comparison of high- z SNe observed in the optical window with local templates at blue and UV wavelengths, hence any uncertainty on the behavior in these bands reflects on the robustness of the conclusions.

2.1 The Issue of Reddening

In general, the light from SNe is absorbed and reddened by interstellar dust both in the Galaxy and in the host system. While the Galactic component is easily removed using maps of the galactic dust distribution [15] and a standard extinction law, more difficult is evaluating the extinction in the host galaxy.

A widely adopted method is to estimate the color excess by comparing the SN color at selected epochs with that of template SNe. In particular, it has been suggested that the B-V color 2-3 months after the explosion is independent on the SN photometric class [6]. In addition to require a fairly good coverage of the SN photometric evolution, this approach relies on the assumption of an

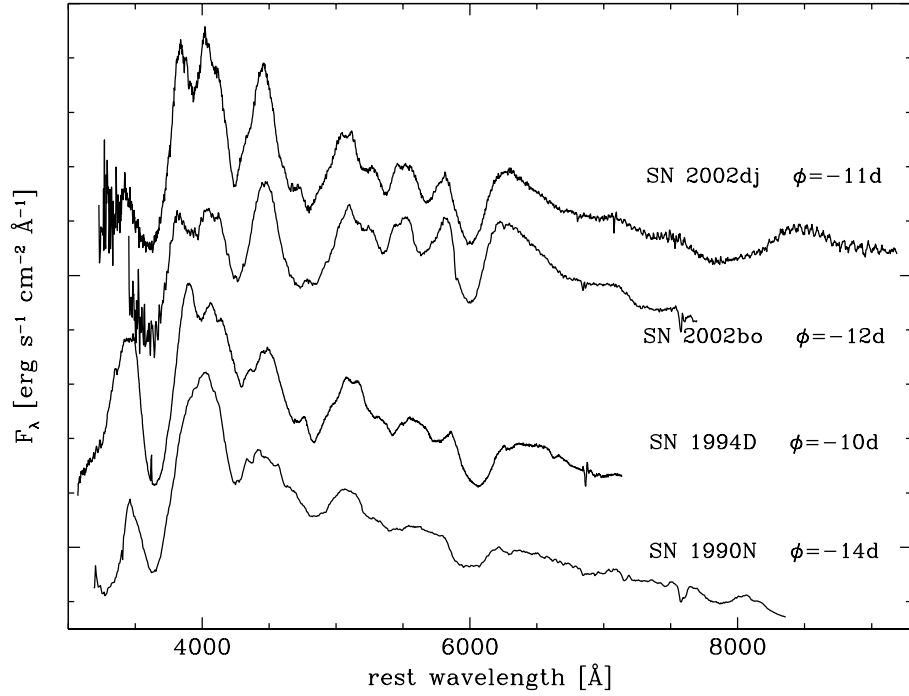


Fig. 2. Comparison of early-time spectra of SNe 2002bo and 2002dj with those of 1990N [14] and 1994D (Wheeler, private communication). The flatter slope of the continuum of SN 2002bo is due to reddening

uniform behavior for all SN Ia which should be checked by some independent measurement.

In principle, high resolution spectroscopy of the interstellar NaID lines by means of the doublet ratio method can give the gas column density which, in turn, can be converted into reddening assuming an average dust-to-gas ratio. However, the method has the drawback that, because of the need to reach a good S/N and a high spectral resolution it can be applied only to few objects, typically nearby SNe observed in proximity of maximum.

An empirical approach has been applied in the past, relating the EW of interstellar absorption lines, measured on medium resolution SN spectra, to the color excess $E(B-V)$ estimated from color curve comparison [16,17]. The first attempts seemed to suggest the existence of a simple linear relation which would imply a constant dust-to-gas ratio, a unique extinction law and a negligible effect of saturation. The latter might be understood considering that because of the galaxy rotation the various absorbing clouds have different radial velocity components along the line of sight. This spreads the interstellar absorptions

at different wavelengths and prevents heavy line saturation. However, with the growth of the event statistics the scatter around the relation appeared to increase significantly and the existence of a relation was questioned.

To review this issues, we have made use of the homogeneous set of $E(B-V)$ estimates for SNIa provided by Phillips et al. [6], integrated by a few more recent objects measured with a similar prescription. For the SNe of this sample we have searched both in the literature and in our archive for high signal-to-noise, medium-resolution spectra and have measured the $EW(NaID)$ of the host galaxy component. With these data we have redrawn the $E(B-V)$ vs. $EW(NaID)$ plot (Fig. 3).

An accurate examination of the figure shows that the points, although apparently dispersed, do not fill the plane but rather seem to cluster around two lines with significant different slopes, and only one or two objects in between. Most objects lie on the line with smaller slope ($E(B-V) = 0.16 \times EW(NaID)$) which roughly corresponds to the previous linear relation [16]. However, there are other SNIa which for similar $EW(NaID)$ are much more heavily reddened ($E(B-V) = -0.04 + 0.51 \times EW(NaID)$). Interestingly, a similar bivariate behavior seems to occur for a sample of SNe of all types also for the Galactic component, where this time the extinction is derived from standard dust maps (open symbols) [15].

The interpretation of this finding is beyond the aim of the present paper and it is more likely related to different conditions of the ISM. Nevertheless it is worth noting that Fig. 3 tells that strong reddening is present each time large values of $EW(NaID)$ are measured in the spectra. In other words, by entering in the graph with a measurement of the $EW(NaID)$ we get lower limits to the reddening of SNIa.

3 Core-collapse Supernovae

Several SN types (II, IIb, Ib, Ic, IIn as well as several peculiar objects) are thought to explode via the gravitational collapse of the core. The great observational diversity has not been fully understood even if it clearly involves the progenitor masses and configurations at the time of explosion. Whereas SN IIP are thought to originate from isolated massive stars, a generalized scenario has been proposed in which common envelope evolution in massive binary systems with varying mass ratios and separations of the components can lead to various degrees of stripping of the envelope [18]. According to this scenario the sequence of types IIL-IIb-Ib-Ic is ordered according to a decreasing mass of the envelope.

3.1 Energetics

In the last few years it has become evident that core-collapse SNe can release different amounts of energy in the explosions. A number of objects with low luminosity and kinetic energy has been discovered (e.g. [19,20]). Although these events are extensively discussed in other contributions to this workshop [21,22],

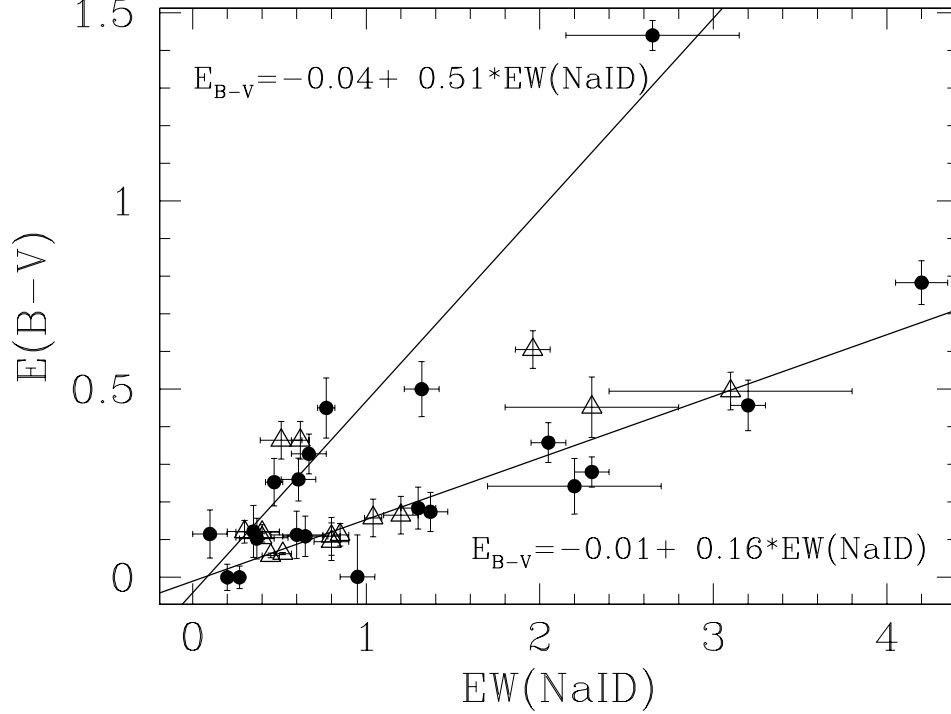


Fig. 3. Color excess of SNIa inside the host galaxy, $E(B-V)$, determined from the tail of the color curves [6], versus $EW(\text{NaID})$ measured on low dispersion spectra (filled circles). The values of SN 1986G (the rightmost point) include also the Galactic component. Open triangles are estimates of Galactic color excess from for SNe of all types [15]

we recall here that they have probably progenitors with $M \geq 20M_{\odot}$. In fact, if the progenitor mass is large enough core collapse may leave a black hole remnant and late time accretion onto the compact remnant can be a significant source of radiation. Unfortunately the optical signature of this event has not been detected yet [23].

On the other end there are super-energetic SNe, often called ‘hypernovae’. The first and most interesting example was SN 1998bw which was discovered while searching for the optical counterpart of GRB980425. SN 1998bw was of type Ic, hence believed to originate from the core collapse of a massive star, stripped of its H and He envelope. It was as bright as a SNIa and the high expansion velocities ($> 3 \times 10^4 \text{ km s}^{-1}$) indicate that it was unusually energetic ($> 10^{52}$ ergs) [24]. Its very powerful radio emission has been attributed to a mildly relativistic blast wave interacting with a clumpy, stratified CSM deriving from a turbulent mass-loss history [25]. Other SNe (e.g. SN 1997ef, SN 1998ey

and SN 2002ap) bear some spectroscopic resemblance to SN 1998bw but are slightly less energetic.

In all these cases the masses of the progenitors estimated by fitting light curves and spectra are larger than in normal core collapse SNe [26]. In a qualitative scenario which may explain this finding, the outcome of the core collapse of stars with $M \geq 20 - 25 M_{\odot}$ results in under- or hyper-energetic explosions, depending on the angular momentum of the collapsing cores. Faint, slowly expanding SNe like 1997D occur because the progenitor envelopes have a large binding energy and relatively little energy remains available for heating up and accelerating the ejecta. Instead if the core of the progenitor is in rapid rotation, owing possibly to the spiraling-in of a companion star, a high energetic, asymmetric explosions may be obtained [27].

An intriguing possibility is that SN 1997cy, observationally classified as SNIIn and possibly the brightest SN ever observed [28,29], and its twin SN 1999E [30], are associated to GRBs. As in the case of other SNIIn, these events show strong ejecta-CSM interaction with explosion energies as high as 3×10^{52} ergs.

3.2 Interaction with the CSM

Very important in determining the outcome of core-collapse SNe is the possible presence of a dense CSM around the progenitor star. Indeed the interaction of the fast ejecta with the slowly expanding CSM generates a forward shock in the CSM and a reverse shock in the ejecta. The shocked material emits radiation in the optical, radio and X-rays with characteristics which depends on the density of both the CSM and the ejecta, and on the properties of the shock [31]. Studying the ejecta-CSM interaction the mass loss history in the late stages of the stellar evolution can be probed.

In some cases it turns out that the interaction begins immediately after the burst indicating that strong wind persisted up to the very last stages of progenitor life. Often the radiation from the shocked region shadows the thermal emission from the ejecta and the spectrum is dominated by strong emission lines with composite profiles, which reflects the different kinematics of the emitting layers. Observationally these SNe are called type IIn.

In most cases, the SN initially expands in an empty space and no interaction occurs. However, in a number of objects the fast expanding ejecta eventually catches the material ejected during remote strong wind events and the SN emission is revived by the interaction. With the noticeable exception SN 1957D, an unclassified, poorly studied object, the optical spectra of late-time revived SNe are dominated by broad, boxy H emission [32,33].

The different behaviors of the flux evolution of $H\alpha$ for a number of CSM interacting SNII is displayed in Fig. 4. In general, type IIn SNe show a slow evolution from the earliest phases and the $H\alpha$ can remain almost constant for years, like in the cases SN 1988Z and SN 1995G [34,35].

The onset of the interaction at late times is evident in the well studied SNe 1979C, 1980K and 1986E [32,33]. After a rather normal evolution in which the $H\alpha$ flux matches the radioactive decay input energy [38] (dotted curve in the left

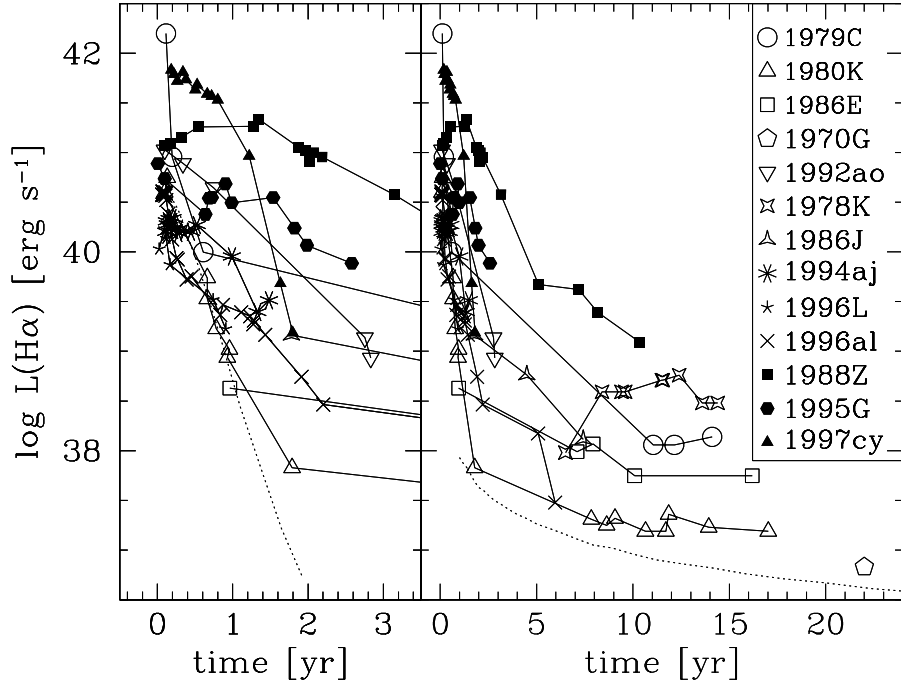


Fig. 4. The long-term $H\alpha$ evolution of interacting SNIIs. On the left panel is shown as a dotted curve the radioactive model [38] while on the right-hand panel is the interaction model for SN 1980K [39]. SNe not following the radioactive model require an additional source of energy, which is provided by the interaction with the CSM. SNIIn (filled symbols) decline slowly starting soon after explosion [40,34,29,35]. Some SNIIs with linear light curves [32,33,36,37,41] (open symbols) show evidence of interaction at late stages. Also the optical observations of the bright radio SNe 1986J and 1978K are reported [42,43] Unpublished data of SN 1992ao, 1996al (ESO 3.6m and NTT) and 1986E (ESO-VLT) come from the Padova archive.

panel Fig. 4), months or years after the explosion the radiation from interaction becomes dominant, the line flux almost halts its decline and the temporal evolution is well reproduced by the circumstellar interaction model (dotted curve in the right panel) [39]. These three SNe belong to the subclass with linear light curves (SNIIL) which are thought to have lost most their hydrogen envelope before the explosion. Therefore, the delayed onset of ejecta–CSM interaction is not surprising. In addition, all of them have been detected in the radio, supporting the claim that late time optical and radio emission are correlated [33]. Similar behaviors, i.e. linear light curves, flattening of the $H\alpha$ flux evolution and boxy line profiles at late time have been exhibited also by SNe 1994aj, 1996L and 1996al,

which showed signatures of slowly expanding shells above the photosphere also in the earliest times [36,37].

Although differences between the observations and the models do exist and improved interaction models are needed, we emphasize that the present observational facilities make possible to study in detail the interaction of the ejecta with the CSM (kinematics, density, temperature the emitting layers) for decades after the explosion which corresponds to probe tens of thousands of years of the progenitor mass loss history.

4 Conclusions

In this paper we have addressed the SN variety. SNIa, which are used as distance indicators up to cosmological distances, can differ as to absolute magnitudes, intrinsic colors at maximum, light and color curve shapes. These differences might be related to the composition and structure of the WD and to variations in the explosion mechanism.

All SNe can be heavily reddened. In the plane $EW(\text{NaID})$ vs. $E(B-V)$, type Ia SNe seem to cluster on two different linear relations, possibly due to different dust-to-gas ratio in the host galaxies. If, on one side this prevents that accurate reddening can be obtained only by means of medium dispersion spectroscopy, on the other there is no doubt that significant reddening is always present when interstellar absorption lines are observed (see Fig. 3).

Core-collapse SNe show a wider variety. Although all ignited by the same event, i.e. the core-collapse, the explosion of progenitors with radii, masses, density structures and angular momenta different up to one order of magnitude can release different amounts of energy and variable amounts of heavy and intermediate mass elements. These, in turn, result in significantly different observables (absolute magnitudes, colors, spectral and luminosity evolution, etc.).

Despite the total number of SNe discovered is well over 2300 [44], there is no doubt that we are still scratching the surface of the SN diversity.

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